Chapter 1

Returning From Space

1.1 The Capability: Exiting the Atmosphere

Exiting the atmosphere into space is an exercise in "brute force." The rocket engines must have thrust that exceeds the weight of the entire vehicle (including propellants) before it can lift off from the launch pad. An exit trajectory is usually very steep (nearly straight up) so the vehicle is well above the dense atmosphere before it accelerates to high speed. Exiting the atmosphere for the express purpose of placing a warhead in a precise location several thousand miles away requires not only "brute force," but also a sophisticated control and guidance system. Exiting the atmosphere to achieve a permanent circular orbit requires the same technology as the warhead delivery. It was only natural that the first orbital flight of a man-made object would be a direct application of missile technology.

To return an object from space is a more challenging task. Friction with the atmosphere creates very high heating at the surface of an object. Shooting stars or meteors are demonstrations of the extreme environment associated with atmospheric entry. [1]Some type of thermal protection is required for objects entering the earth's atmosphere.

1.2 The Challenge: Atmospheric Entry

The term "Lifting Body Program" usually refers to a flight test program conducted between 1963 and 1975 at Edwards, California on a strange looking family of wingless aircraft. The reason for these unusual configurations is found in the challenge to design a manned vehicle which would survive entry into the earth's atmosphere. Three factors would affect the design of a manned entry device:

---

[1] The terms "entry" and "reentry" are often used interchangeably in the industry. In this document the term "reentry" refers to a suborbital maneuver where the path and environment back through the atmosphere are dictated by the launch trajectory; the flight from launch to landing can be viewed as a single maneuver. The term "entry" refers to a maneuver which is initiated from orbital or super-orbital conditions where the path and environment back through the atmosphere are created independently from the launch trajectory.

(1) Intense heat generated by friction with the earth's atmosphere,
(2) High accelerations, and resulting "g" loads [2] associated with the rapid loss of speed during entry,
(3) Selection and control of the initial entry angle (relative to the horizontal) which would dictate the heat and g loads (Figure 1-1).

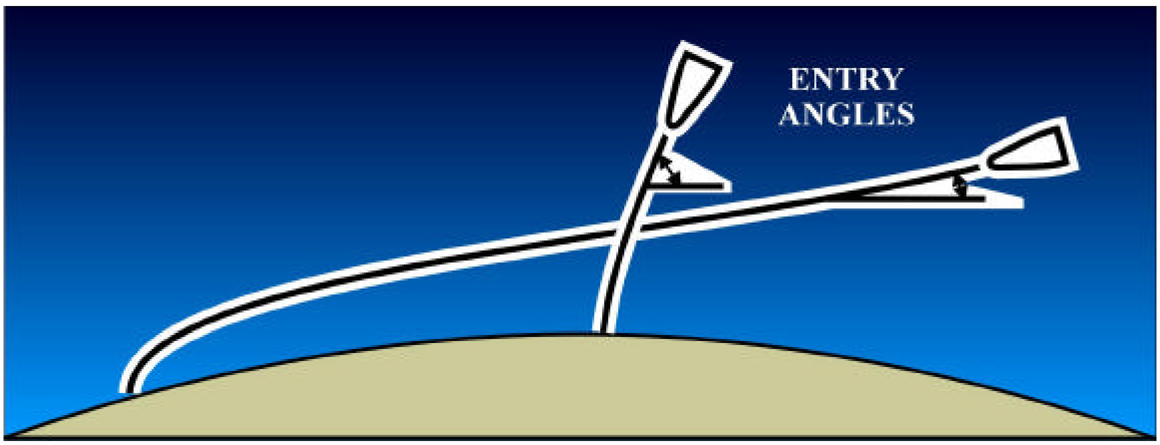

Figure 1-1: Entry Angle

These three factors are related to each other and they offered the early entry vehicle designers some trade-offs. Steep entry angles were known to produce very high g loads. The time of entry would be very short, however, and, although temperatures were expected to be extremely high, there were known methods for handling the short heat pulse. This entry method was appropriate for ballistic missile warheads but g loads were far too high for human survival (100 "g" or more). Shallow entries could be tailored to produce lower g loads but would result in a longer entry time. Peak temperatures were expected to be lower but the longer duration heat pulse was an additional design challenge. There was a very narrow range of entry angles which would provide acceptable g loads for human survival, and these required very careful trajectory control at the beginning of the entry. Thus there was reason to believe that a ballistic entry could be tailored to allow a manned vehicle to survive entry through the atmosphere.

---

[2] .."g" loads are those forces affecting the vehicle and its occupants resulting from rapid changes in speed (accelerations or decelerations). The normal measure of "g" load is the "load factor" or "g" which is the ratio of the force experienced under acceleration to the force that would exist if the object was at rest on the surface of the earth.

1.3 Ballistic Entry

A ballistic entry is one in which the force created is always parallel to the line of flight, that is, a "drag" force. The trajectory is always in the form of a parabola and represents the balance of forward speed with the earth's gravity. Baseballs, arrows, bullets and artillery shells follow ballistic trajectories but their velocities are too low to induce significant atmospheric friction. The primary design parameter for ballistic entry is the Ballistic Coefficient;

Ballistic Coefficient = Weight/(Drag Coefficient x Area)

Heating and deceleration are less intense for a low Ballistic Coefficient (low weight and/or high drag and large frontal area) than for a high value since the entry occurs high in the atmosphere where the air is less dense (Figure 1-2).

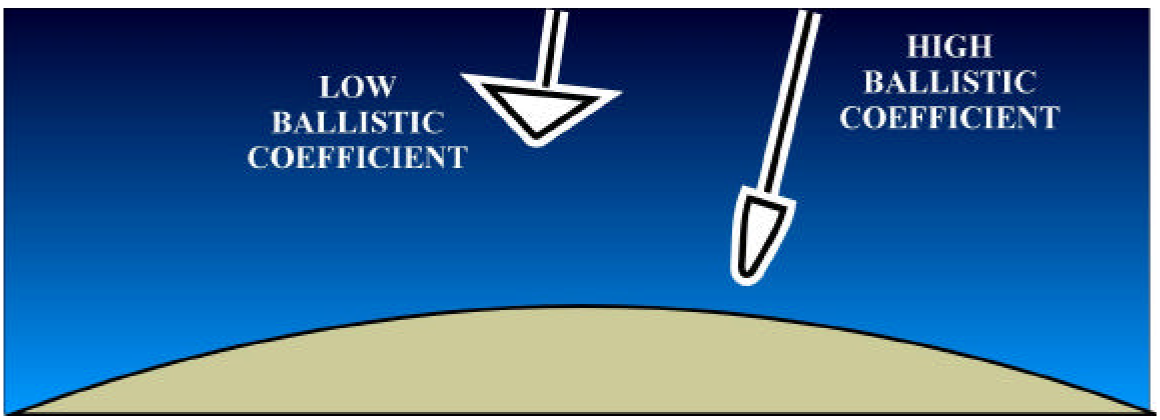

Figure 1-2: Ballistic Coefficient

Early Inter-Continental Ballistic Missiles (ICBM's) utilized this reentry method. Thermal protection for these early warheads was a massive metallic heat shield which merely provided a "heat sink" for the short heating pulse. It was soon discovered that delivery accuracy could be improved by increasing the values of the Ballistic Coefficient thus increasing the impact velocity so that the final descent phase was less affected by winds. Thermal protection was provided by allowing the material at the surface of the heat shield to melt or vaporize thus transferring much of the heat back into the atmosphere. This method of thermal protection is referred to as "ablation," and the material that is applied to the vehicle's outer surface is called an "ablator."

The development of missile warheads was the primary technological goal of the fifties, and significant progress in the development of ablators was accomplished as a result. Early designs for manned entry vehicles took maximum advantage of the missile warhead technology. By using low Ballistic Coefficients and shallow entry trajectories the g load could be maintained within the human tolerance level. This resulted in a longer time for a manned entry, however, and thus required a thick layer of ablation material on the outer surface.

The initial entry angle (determined by the capsule attitude at retrofire) was quite critical and, at best, the g loads were almost incapacitating to the crew (approximately 8 "g" for about a minute and a half). Centrifuge studies had shown that the human tolerance to long periods of high g loads was greatest if the subject was in a reclining position and the force was applied from front to back (that is, "eyeballs-in"). Manned ballistic entry capsules were therefore designed to position the crew member(s) lying on their backs facing away from the direction of flight (Figure 1-3).

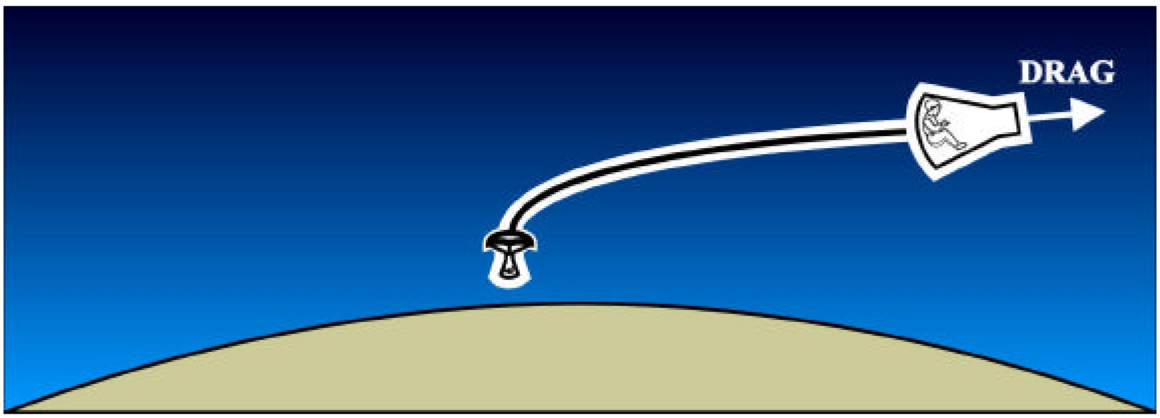

Figure 1-3: Ballistic Entry

During the final phase of a manned, ballistic entry some type of auxiliary device was necessary to slow the vehicle to a very low sink rate at the moment of impact with the earth (parachute, rotor, landing rocket, etc.). This entry vehicle concept was commonly referred to as the "Decoupled Mode" since the aerodynamic features necessary for the atmospheric entry were different (or "decoupled") from those necessary for final landing. The Mercury program was the only U.S. manned entry program to utilize a pure ballistic entry trajectory. A parachute was used for the final landing (Figure 1-3). Even before the first Mercury flight it was recognized that the pure ballistic entry was too critical for an "operational" (that is, routine and low cost) manned entry system. In addition to the g load and heating criticality of the entry, the poor predictability of the final impact point led to the selection of ocean landing areas requiring a rather large contingent of ships and helicopters for recovery as evidenced by the Mercury program.

Some improvement in the recovery accuracy was possible by adding maneuverability to the second, decoupled phase. A maneuverable parachute concept (Rogallo wing) was explored as a potential improvement for decoupled mode entries, but it has never been incorporated in any U.S. manned system. The concept, however, has continued to evolve. Recently, successful low speed demonstrations of parachute recoveries of small, unmanned entry shapes have been made using high-lift parachutes.

1.4 Semi-Ballistic Entry

By providing a small amount of "lift" during entry, that is, an aerodynamic force perpendicular to the flight path, the severity of the entry could be reduced substantially and the recovery accuracy could also be improved. Lift was created by offsetting the center of gravity of the entry vehicle slightly so that the blunt face of the heat shield was inclined at an angle to the flight path (Figure 1-4).

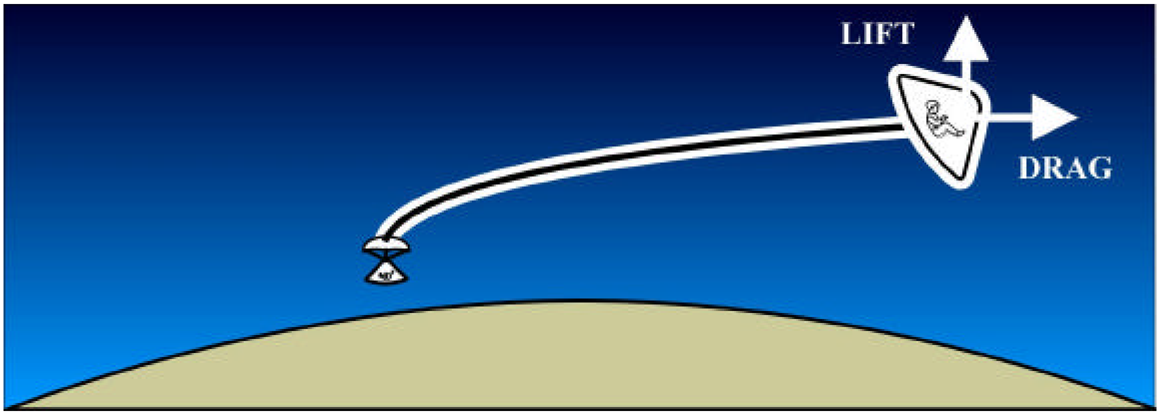

Figure 1-4: Semi-Ballistic Entry

By controlling the bank angle during entry, the lift could be directed to control the flight path. Initially the lift could be directed upward to maintain a small flight path angle as long as possible. Once the vehicle passed the high speed heating pulse, it could be banked to turn toward the desired recovery point. After achieving the heading to the target recovery point, a continuous roll could be introduced to cancel the lift effects and thereby simulate a pure ballistic trajectory for the remainder of the entry.

The resulting semi-ballistic entries were of longer duration than a pure ballistic entry, but produced somewhat lower g loads and lower peak temperatures. The design of the ablator heat shield was more complex since the heating was not symmetrical on the heat shield and the duration of high heating was somewhat longer. A modified ablator, called a "non-receding, charring ablator," evolved. At high temperature the material burned and released hot gases, but the char stayed in place and maintained the outer contours of the surface. In this way the aerodynamic and lifting capabilities of the shape were retained. The material was molded into a honeycomb grid during construction to help control the shape of the char. When the ablator was used in sufficient thickness the combination of char and virgin ablator material provided an effective insulation blanket during entry and thus allowed the use of common materials for the sub-structure (steel, titanium or even aluminum). The semi-ballistic entry gave the entry vehicle designer more latitude for design trade-offs. The trajectory could be continuously adjusted throughout the entry for control of both heating and recovery location. The g loads on the human crew were no longer a limiting factor; however, the semi-ballistic entry still required the reclined, aft-facing crew position and a parachute or some other type of "decoupled mode" recovery device.

The Gemini and Apollo capsules employed semi-ballistic entry designs using non-receding, charring ablators, and both used non-maneuverable parachutes and water recovery for the final de-coupled phase. Of course all of the ballistic and semi-ballistic concepts discussed thus far were designed to survive a single entry. Although technically feasible, major refurbishment would have been required to refly any of the vehicles.

1.5 Lifting Entry

A lifting entry is one in which the primary force being generated is perpendicular to the flight path, that is, a "lift" force. Although drag is present throughout the entry, the resulting flight path can be adjusted continuously to change both vertical motion and flight direction while the velocity is slowing. The gliding flight of a sailplane is an example of "lifting" entry without high velocities and heating. The primary design parameter for lifting entry is the Lift to Drag Ratio, or L/D;

L/D = Lift/Drag

Low values of L/D produce moderate g loads, moderate heating levels and low maneuverability with moderate entry duration's (essentially the same as the semi-ballistic entry). High values of L/D produce very low g loads, but entries are of very long duration and have continuous heating. Although the peak temperatures of a lifting entry are below the peak temperature of a ballistic entry, the total heat load that must be absorbed over the duration of the entry is higher. Lateral maneuverability during entry (commonly referred to as "cross-range capability") is dramatically increased as the L/D increases.

A secondary, but important, parameter for lifting entry is the Wing Loading;

Wing Loading = Weight/Projected Area

The Wing Loading for a lifting entry is comparable to the Ballistic Coefficient for a ballistic entry with a similar effect. Low Wing Loadings (low weight and/or large projected area) cause the deceleration and heating to occur high in the atmosphere. Heating and deceleration are less intense for a low Wing Loading (similar to low Ballistic Coefficients).

The lifting entry promised improved conditions for crew members during entry. The g loads of a lifting entry were expected to be so low (approximately 1.5 "g") that the crew members could be seated in a normal aircraft-like fashion facing the direction of flight. It was also expected that the crew could function normally throughout the entry without concern for even a temporary loss of consciousness (Figure 1-5).

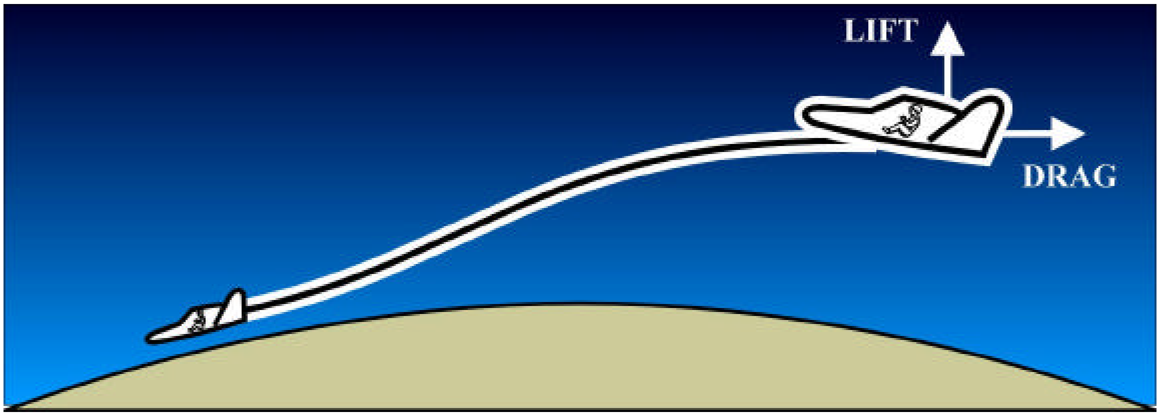

Figure 1-5: Lifting Entry

One of the advantages foreseen for a lifting entry vehicle was the high probability that the vehicle could be landed like a normal glider after completing the entry. This would eliminate the need for parachutes or other "decoupled mode" recovery concepts. Theoretical and wind tunnel studies, however, showed that the aerodynamic configurations which produced the highest L/D at very high Mach number during entry did not necessarily produce "high" L/D at landing speeds. The highest L/D's during entry were produced by long slender cones or wedges without wings. The highest L/D for landing was, of course, obtained with a long, glider-like wing. Compromises were soon found in the form of delta-wing configurations (triangular wing planforms) with moderately high L/D during entry yet also with the capability to land on a normal runway. Wing loading also had an effect on the land-ability; low wing loadings resulted in slow landing speeds and high wing loadings resulted in high landing speeds.

Thermal protection concepts for lifting entry were more challenging than the ballistic and semi-ballistic methods due to the longer entry time. Early thermal protection methods (of the late 1950's) revolved around two basic concepts: (1) "Active cooling" concepts which circulated fluid through the hot area, then through a radiator, much like the engine cooling system for an automobile; and (2) "Passive or Radiative cooling" concepts which used thin, high-temperature materials that reached an equilibrium temperature by radiating the heat away from the surface, much like the heating element of a stove. The ceramic tiles or fire brick then available were brittle and far too heavy to be seriously considered. Both active and passive thermal protection methods could be reusable with little if any refurbishment required, but both were complex and dependent on the successful development of high temperature materials.

The lifting entry concept gave the entry vehicle designer even more latitude for design trade-offs than ballistic or semi-ballistic entry concepts. A reusable entry vehicle capable of landing on a normal aircraft runway was seen as a key to increasing manned access to space at a reasonable cost.

1.6 Emergence of the Lifting Body

The entry concepts described thus far have been portrayed in a sequence that shows an increase in complexity (from pure ballistic to lifting), and a parallel increase in capability or utility. The knowledge of these different interactions and trade-offs did NOT emerge gradually as different vehicles were built and tested. All of these factors and trade-offs were well known by the late 1950's as a result of pioneers in the field, such as Alfred J. Eggers and H. Julian Allen of the National Advisory Committee for Aeronautics (NACA) Ames Research Center (ARC) (Reference Syvertson, 1968). The technology required to implement the more complex (but more useful) lifting entry methods, however, was not yet fully developed or proven.

The application of available "ablator" technology appeared to provide a means for near-term manned space flight. The question that arose was:

Could a low L/D lifting entry vehicle be developed that would use the available thermal protection methods of the non-receding charring ablators, yet still have sufficient low speed L/D so it could land safely?

The use of ablator technology would limit the allowable time for entry and thus the maximum useful entry L/D to a value of about 1.0. The use of ablators would also constrain the value of the entry L/D to a relatively narrow range around the nominal value of 1.0. This entry L/D was easily achievable by a variety of blunt-nosed, wingless entry shapes. The answer to the second part of the question was less obvious. Designers proposed modifications to several of these entry configuration shapes which would hopefully allow them to perform horizontal landings (Figure 1-6).

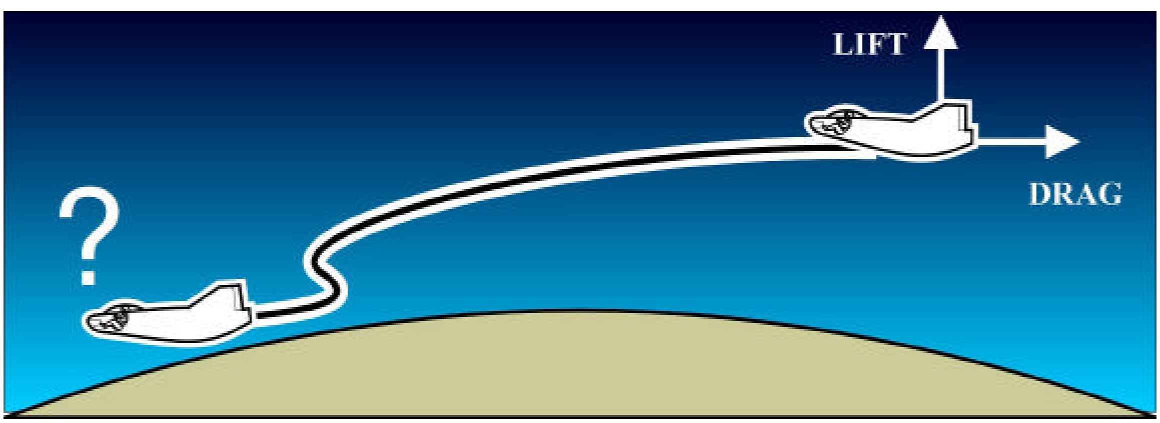

Figure 1-6: Lifting Body Entry

A brief flight test program was conducted on an F-104 by the National Aeronautics and Space Administration (NASA) Flight Research Center (FRC) in 1959 (Reference Matranga, 1959) to explore low L/D landing methods. If landings were feasible, a lifting body vehicle could be used in the near term to demonstrate the primary advantages of lifting entry without being dependent upon the development of the exotic materials or systems necessary for a high L/D entry vehicle.

The "Lifting Body Program" was conceived to answer the land-ability question regarding these proposed entry configurations. The program called for the construction of low cost, all-aluminum airframes that would not include thermal protection systems, or other subsystems, necessary for an actual entry. The program addressed concerns not only for the low speed L/D and land-ability, but also for the transonic stability and control of these blunt shapes as they decelerated through the critical transonic speed regime.

1.7 Glider Landing Techniques

Lifting entry vehicle designers gave serious consideration to including a propulsion system for landing. Although landing engines would allow a vehicle to land like a normal airplane, the powered approach was not an attractive alternative due to the added weight and complexity. Before beginning a discussion of the individual projects, it is, therefore, appropriate to describe simply the techniques used to land unpowered airplanes.

All gliders, whether they are sailplanes (L/D’s from 25 to 50) or lifting bodies (L/D’s from 2.8 to 5.0), use the same general strategy to perform safe and accurate horizontal landings. The energy possessed by an airplane is of two forms: potential energy (altitude above the ground) and kinetic energy (forward velocity relative to the ground). Unlike a powered airplane which can add energy or maintain a constant energy level, a glider is constantly losing energy. Potential and kinetic energy can be traded with each other. A constant-speed glide loses only potential energy while a slow-down at constant altitude loses only kinetic energy. The pilot must control the loss of energy so that he arrives at the desired landing point at zero altitude and at the proper landing speed. There are three primary methods used to control energy: speed, landing pattern geometry, and drag-producing devices (speed brakes). The usual philosophy for performing a safe glider landing is to give up potential energy for an increase in kinetic energy as the glider gets closer to the ground; that is, increase speed by allowing the approach angle to steepen. Since speed can be quickly dissipated near the ground by drag devices, this excess speed allows for last minute pattern corrections for winds or other anomalies. Although the general technique for landing a lifting body is similar to that of a sailplane, there is an enormous difference in the levels of energy involved. The development and perfection of this energy exchange to achieve a controlled, accurate landing were primary objectives of the Lifting Body Program.